Multi-attribute Visualization and Improved Depth Perception for the Interactive Analysis of 3D Truss Structures

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Abstract

In architecture, engineering, and construction (AEC), load-bearing truss structures are commonly modeled as a set of connected beam elements. For complex 3D structures, rendering beam elements as line segments presents several challenges due densely overlapping elements, including visual clutter, and general depth perception issues. Furthermore, line segments provide very little area for displaying additional element attributes. In this paper, we investigate the effectiveness of rendering effects for reducing visual clutter and improving depth perception for truss structures specifically, such as distance-based brightness attenuation and screen-space ambient occlusion (SSAO). Additionally, we provide multiple options for multi-attribute visualization directly on the structure and evaluate both aspects with two expert interviews.

CCS Concepts

• ***Computing methodologies*** → *Rendering;* • ***Human-centered computing*** → *Visualization;*

1. Introduction

Performance evaluation of design variants is an important aspect in architecture, engineering, and construction (AEC) [AAB*22]. This is especially the case for adaptive truss structures that are capable of autonomously manipulating stresses and deformations from adverse influences [BHW*22]. The degree to which a structure can perform such manipulations, however, is directly related to its topological layout. Therefore, it can be beneficial to researchers investigating such topologies to be able to view multiple performance attributes at the same time and to display them directly in the 3D context of the structure to find spatial patterns and possible correlations. In a collaboration between domain experts from architecture and visualization experts, this work explores the feasibility of visualizing per-element attributes directly on the 3D representation of a truss structure. The structures are commonly modeled as a set of connected beam elements, which we render as line segments. To fit the visualization into the interactive workflow of our domain experts, and link them to the computer-aided design (CAD) applications used by them [Rob23], we focus on real-time rendering techniques. Figure 1 shows the truss structure data set that we investigated for this paper, using different rendering options and attribute visualizations. As can be seen, the elements heavily overlap in screen-space, which causes visual clutter and occlusion of elements. Without the help of additional depth cues, such as lighting effects, depth perception and understanding the spatial layout of the structure are challenging. At the same time, the line geometry offers only limited drawing area for visualizing multiple attributes.

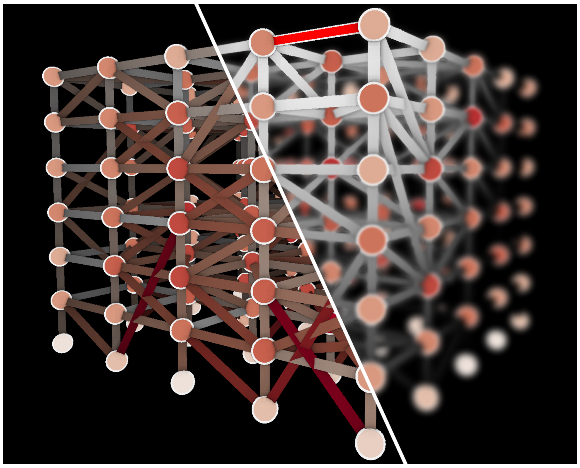

Figure 1: *Visualization of a truss structure with different rendering options.* Left: *SSAO and brightness attenuation for improved depth perception. Attribute values are mapped to color on beam elements and to fill-color of the nodes.* Right: *Defocus effect and brightness attenuation divert attention from the background to the selection.*

The aim of our work is to (1) provide a rendering of 3D truss structures with reduced visual clutter and improved depth perception; (2) contribute methods for visualizing multiple attributes at the same time directly on the structure; and (3) perform a preliminary evaluation of the effectiveness of the rendering and visualization methods with two expert interviews.

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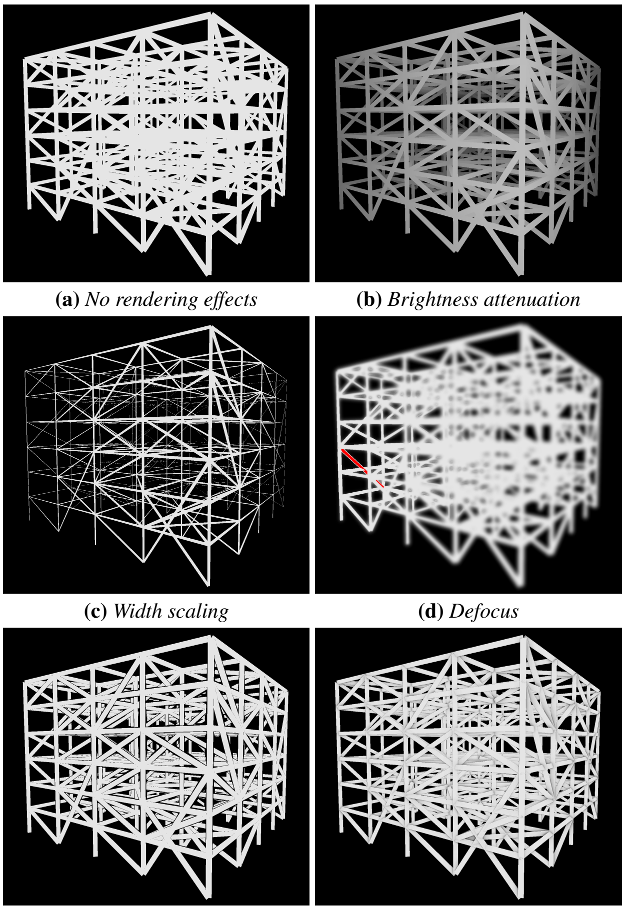

(a) *No rendering effects* **(b)** *Brightness attenuation* **(c)** *Width scaling* **(d)** *Defocus* **(e)** *Depth-dependent halos* **(f)** *Screen-space ambient occlusion*

Figure 2: *Different rendering methods for adding depth cues.*

2. Related Work

Dense Line Rendering. Dense line rendering is a common problem in graph visualization, and there are many approaches for avoiding visual clutter in 2D space, e.g., different edge representations in directed 2D node-link diagrams [HIvWF11], rendering of graph edges in augmented reality [BVD19], or optimizing the blending order in line charts [TB21]. In contrast to graph visualization and line charts, the elements of a truss structures have fixed locations and order and the shape of elements should not be completely warped. Stoll et al. [SGS05] improve the depth perception of lines for 3D vector field visualization using modified Phong lighting and shadow rendering, and similar cues can be included in 3D texture-based rendering [FW08]. Everts et al. [EBRI09] use depth-dependent halos to improve the depth perception of dense 3D line data, a technique we adopt for the rendering of truss structures. For dense bundles of lines, Eichelbaum et al. [EHS13] use an optimized ambient occlusion method to improve spatial perception.

Multi-attribute Visualization. Liu et al. [LMW*17] provide an overview of methods for visualizing high-dimensional data in general, and Urness et al. [UIL*06] a collection of strategies for multi-attribute flow visualization. Frequently, multi-attribute visualizations use glyph-based techniques [BKC*13]. Each glyph offers multiple visual channel such as position, size, color, and shape for visualizing multiple attributes at the same time. In the context of truss structures, each beam element can be considered a glyph. However, the fixed geometrical layout limits shape changes and complex textures are difficult to display on the limited surface area. Often, only color is used to visualize an attribute on line renderings [BVD19]. For the visualization of stream lines, Stoll et al. [SGS05] use color and radius to visualize velocity and divergence, while texture is used to show rotation.

3. Improving Depth Perception

We render truss structures as a set of 3D line segments and nodes, implicitly defined at locations where two or more lines meet. Each line segment is displayed as a quadrangle that always faces the camera to allow arbitrary line width. Nodes are rendered as raycasted spheres using billboards. Rendering 3D scenes on a 2D mono display heavily relies on monocular depth cues to convey spatial relationships in the scene. We implemented the following methods to add depth cues and to investigate their effectiveness for the specific use-case of a truss structure.

Distance-based Effects. Depth can be indicated by changing the appearance of surfaces directly proportionally to their Euclidean distance to the viewer or another reference point. We investigate three distance-based rendering effects. To smoothly ease effects in and out, we define the following normalized distance value: $v = 1 - smoothstep(0, d_{\max}, d)$, where *smoothstep* performs a Hermite interpolation [Khr14], $d_{\max}$ denotes a user-defined maximum distance, and d denotes the distance from the surface to the camera or the focus point within the scene set by the user.

- **Brightness attenuation** based on distance invokes a visual effect similar to aerial perspective or light falloff. Reducing brightness blends the rendered line segments toward the dark background color (see Figure 2b). To keep lines from vanishing completely if the distance becomes too large, users can either adjust $d_{\max}$ or specify a minimum value to clamp the brightness.
- **Width** of the elements is scaled with distance v to imitate and exaggerate the effect of objects becoming smaller at increasing distance from the camera due to linear perspective projection. (see Figure 2c). To make it more pronounced, we use the modified distance $v' = v^3$. To keep lines from vanishing completely, users can adjust $d_{\max}$ or specify a minimum element width.
- **Defocus** effects or depth-of-field are frequently used for artistic purposes in computer graphics both to convey scene depth and to direct attention. We highlight a region around a user-selected focus point by increasingly blurring the remaining structure with growing distance from the focus region (see Figure 2d). Our implementation is derived from screen-space approximation of the circle of confusion in thin lens models [ST05].

Ambient Occlusion. Surface shading and lighting are important depth cues for spatial perception [Gro16]. To approximate global lighting and improve depth perception in virtual scenes, screen-space ambient occlusion (SSAO) [Mit07] is widely used in visualization and computer graphics. Occlusion of surface points is approximated by randomly sampling the upper hemisphere around the point and testing the sample positions against the corresponding value from the depth buffer to determine if nearby geometry occludes the surface. Figure 2f shows the result of using SSAO for rendering the truss structure.

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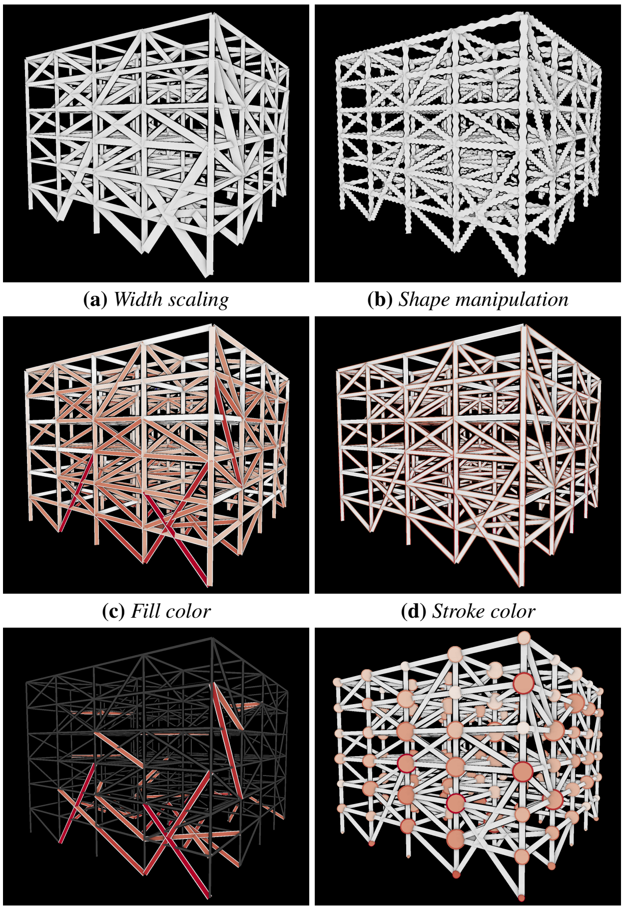

(a) *Width scaling* (b) *Shape manipulation* (c) *Fill color* (d) *Stroke color* (e) *Filtered elements* (f) *Node visualization*

Figure 3: (a)–(d) *Different visual channels.* (e) *Filtering based on value range for a selected attribute.* (f) *Node fill and stroke color show average and maximum value of an attribute for adjacent elements. Size shows valence, i.e., the number of adjacent elements.*

Depth Halos. Depth-dependent halos [KRH*06] [EBRI09] improve the depth perception by extending line geometry with an additional border stroke that is drawn using the background color and occludes line geometry that overlaps in screen space but is rendered at greater distance from the camera. Furthermore, the added border is thinner if overlapping lines are in close proximity in 3D space and becomes thicker otherwise (see Figure 2e).

4. Multi-attribute Visualization

Visual channels such as position, shape, color, and size can be used to display the geometry of a truss structure and to visualize multiple additional attributes of the elements and nodes. Texture, orientation, fuzziness, and transparency can also be considered [Rot17]. In this paper, we take multiple per-element attributes from the redundancy matrix [vRB21, KvSG*22], which gives information on the distribution of statical indeterminacy, as well as additional topological attributes. Visualizing multiple attributes at the same time requires the combined usage of several visual channels.

Visual Channels. In the context of 3D visualizations of truss structures, position, orientation, and length of the elements are fixed by the geometry of the structure and unavailable for visualizing arbitrary attributes. Also, element shape can only be modified to a certain degree to visualize attributes and perspective rendering further limits available options as complex or oriented shapes can be difficult to clearly recognize depending on viewing angles. The inherently slim silhouette of beam elements also drastically limits the drawing area available to visualize attributes via color or texture. Especially if element width is used as a visual channel at the same time, clearly recognizing distinct colors or textures can be severely impaired. Further, mapping attributes to element width potentially clashes with perspective rendering. A far-away element that has larger width due to a high attribute value might be confused with an element close to the camera but with a smaller width due to a low attribute value. This interferes with both the spatial perception of the structure and with reading attribute values.

Beam Elements. In total, up to four attributes can be visualized on the elements at the same time using different visual channels. Users can freely map attributes to visual channels and it is possible to assign the same attribute to multiple channels. It is also possible to define a value range for an attribute to filter elements, as shown in Figure 3e. Furthermore, some attributes depend on the currently selected element. The following visual channels are available:

- **Element width** is scaled proportionally to attribute values. Using global maximum and minimum values for the attribute, we first compute normalized values $\hat{a}_i$ and then use them to scale the element width between a user-defined minimum and maximum width: $w_i = \hat{a}_i(w_{\max} - w_{\min}) + w_{\min}$ (see Figure 3a).
- **Element shape** is used as a visual channel by varying width along the line segments using a cosine function $g(x) = 0.5(-\cos(2\pi x) + 1)$ and modulating the frequency by $\hat{a}$. The modified width is computed as $\hat{w}_i(l) = 0.7w_i + 0.3w_i g(m\,l\,\hat{a})$, where l denotes the linear location between start and end point of the element and m denotes a base frequency. At most 30% of the base width w_i are used for this effect (see Figure 3b).
- **Fill color** and **stroke color** provide two visual channels. Fill color covers the inner area of the elements while the stroke color is used for the outline. Different transfer functions can be used to visualize attributes with a diverging, sequential, or qualitative scale. As the redundancy matrix entries are signed, we use a bent cool–warm color transfer function [Mor09] by default. Figure 3c and 3d show fill color and stroke color being used and it is easily visible that all values are positive for the shown attribute.

Nodes. In total, up to three attributes can be visualized on the nodes at the same time using the following visual channels:

- **Radius** is used identically to width for elements.
- Color is split into **fill color** and **stroke color**. Figure 3f shows an example of all three visual channels being used on the nodes.

5. Expert Interviews

To gain an impression of how effective the proposed methods for improved depth perception and multi-attribute visualization are in the specific context of truss structures, we conducted two expert interviews. The first expert (*E1*) comes from the architectural domain and is also a co-author of this paper. The second expert (*E2*) comes from the visualization domain. While *E1* focused primarily on gaining insights for understanding the redundancy matrix, *E2* commented mostly on the visualization techniques in general and their effectiveness. The application was presented to the experts in the following order: First, we briefed the experts on the available rendering options (see section 3). Then, the multi-attribute visualization (see section 4) on the beam elements was introduced and finally the node visualization. Before moving on to the multi-attribute visualization, the experts chose which rendering methods to use. They could adjust the rendering options at any time during the remaining interview. We asked the experts to freely explore different mappings of the quantitative values provided by the redundancy matrix without specific tasks, as finding meaningful metrics and mappings for the matrix is still subject to ongoing research.

Depth Perception. *E2* considered depth halos to be useful to tell foreground and background beam elements apart and to better distinguish individual elements in dense areas. However, they considered distance-based brightness to be more effective, as it does not only help to tell elements apart, but also makes it easier to assess their position in space. At the same time, *E1* pointed out that distance-based brightness hides large parts of the structure and therefore some context is lost. Especially if brightness is attenuated relative to a selected focus point, it becomes difficult to inspect areas at the far end of the structure while keeping the selection active. *E1* stated that the defocus effect retains more context compared to distance-based brightness, as the whole structure remains visible. However, the experts considered the high amount of blurring to be visually taxing, especially when selecting elements at the far end of the structure, which causes visual artifacts for elements located between the focus region and the camera. *E1* considered distance-based width to be useful as long as no attributes are visualized on the beam element, since screen-space coverage of the elements becomes very small and attributes become difficult to read. *E2* observed that differentiating elements that are close to one another is improved by SSAO. They also pointed out that the foreground of the structure could be viewed more distinctly when using distance-based brightness compared to using only SSAO, for example for elements parallel in screen-space but located at different depth. Both experts found the combination of distance-based brightness and SSAO to be very practical. *E2* also praised the combination of distance-based brightness, distance-based width, and SSAO. *E2* saw little benefit in additionally using depth halos, but when using only SSAO and depth halos, the impact of the depth halos was perceived to be more noticeable. For exploring the multi-attribute visualizations, *E1* initially chose depth halos, distance-based brightness, and distance-based width. However, they immediately deactivated distance-based width and chose not to reactivate it even when width was not used as a visual channel. *E2* decided to use distance-based brightness and SSAO for the second stage of the interview. Both experts eventually selected this combination and identified it as the most effective and favorable option.

Multi-attribute Visualization. *E2* observed that color is better suited to identify redundant elements in the structure compared to line width. Different colors of adjacent and overlapping elements also help see their position and spatial arrangement. *E1* observed that with color, outliers are immediately noticeable. Nevertheless, they expressed the wish to view exact values of elements, suggesting that while color is a good indicator, a detailed inspection would benefit from displaying exact value, e.g., when selecting an element. Concerning stroke color, *E2* stated that it is primarily useful to detect discontinuities and homogeneous regions by tracing matching colors throughout the structure. The same is possible with fill color, but separately color-mapping both the outline and center of elements makes it possible to visualize two different values at the same time. According to *E1*, detecting differences between topological and Euclidean distances of elements is easier using element shape rather than mapping it to color. That is, in areas with generally weak curling, elements with strong curling stand out more prominently. However, small difference in value are difficult to recognize based on shape, e.g., elements of topological distance 1 are visually very similar to elements of distance 2. *E1* noticed that mapping an attribute to multiple visual channels at the same time emphasizes discontinuities and homogeneous regions. This was especially useful to them when parts of the structure were put in focus and remaining parts less visible, e.g., due to selection-based brightness attenuation. For the node visualization, *E1* found the usage of fill color, stroke color, and size for different attributes to be particularly helpful.

General Settings and Filtering. Both experts reduced element base width to put greater emphasis on the nodes when these were shown. In this context, *E2* expressed the desire to completely disable rendering the beam elements. Having the option to set a minimum and maximum value for the element width was very helpful to *E1* when using width as a visual channel. Other visual channels would benefit from this option as well, e.g., to limit the range of the shape modulation on elements to make finer differences easier to distinguish. Filtering elements was well-received by both experts. It allowed them to highlight specific value ranges while retaining the spatial context of the structure. Still, *E1* noted that elements that had been filtered out remained fairly noticeable and partially occluded other elements. Adding transparency might resolve this issue. Currently, the transfer function for color mapping does not change when filtering elements. It would be desirable to adjust the minimum and maximum values of the transfer function based on the non-filtered elements. Furthermore, both experts stated that filtering should also be available for nodes to improve the visibility of nodes in the interior of the structure.

6. Conclusions and Future Work

We presented an approach for multi-attribute visualization on truss structures rendered as 3D line segments. To that end, we discussed the availability of visual channels on the structure and proposed concepts for using them. To reduce visual clutter and improve depth perception we implemented and discussed the use of several rendering effects, including distance-based attenuation, defocus, SSAO, and depth-dependent halos. We performed an initial evaluation of the implemented rendering effects and multi-attribute visualization by interviewing two experts from architecture and visualization, respectively. In the future, we plan to improve our approach by refining the rendering effects, investigating better attribute mappings, and assessing additional visual channels. We also plan to interview more experts, specifically including civil engineering as well, and to identify the tasks most relevant to them.

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